

# Energy Dependence of the $v_2$ -scaling and the QCD Phase Boundary

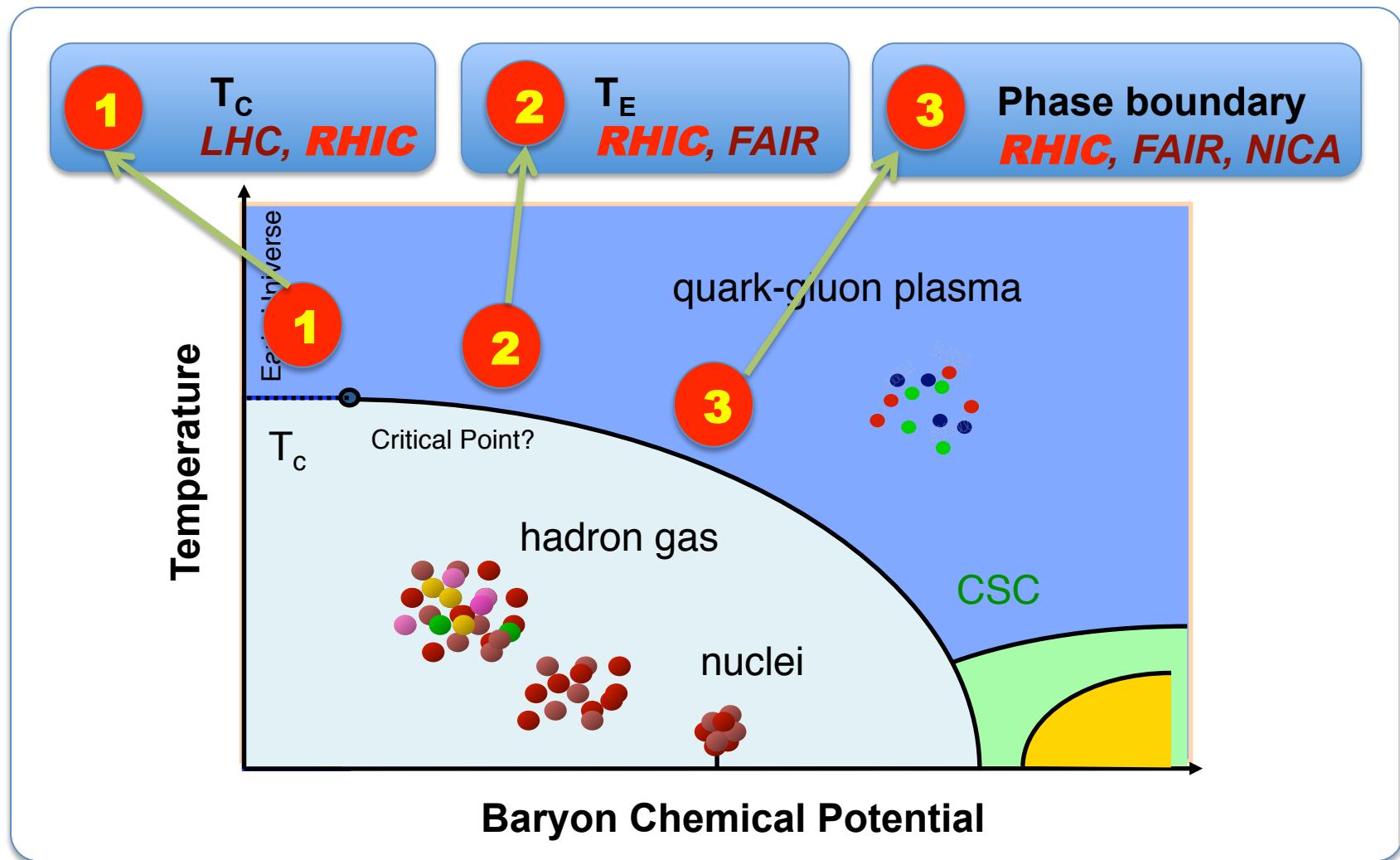
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*Many Thanks to the Organizers!*

# The QCD Phase Diagram and High-Energy Nuclear Collisions





# Outline

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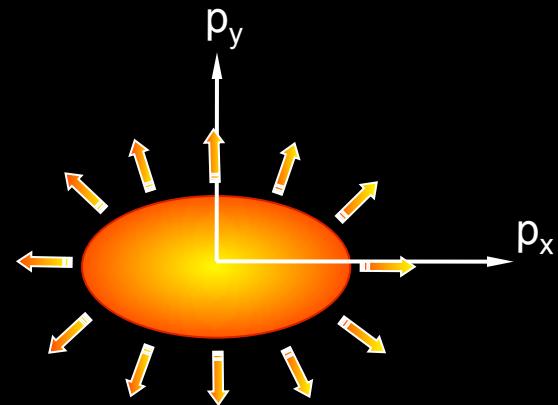
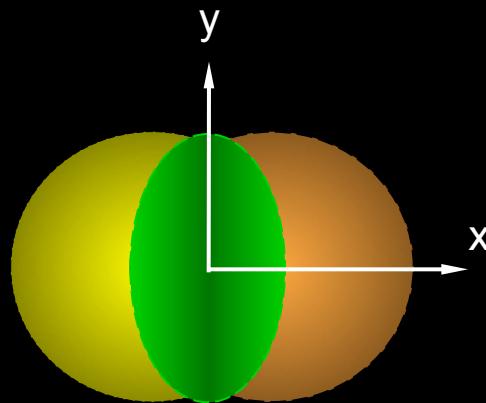
- (1) Introduction
- (2) Recent  $v_2$  results from RHIC
- (3) A proposal: using NQ scaling in  $v_2$  for locating the possible QCD phase boundary
- (4) Summary and Outlook

# Anisotropy Parameter $v_2$

coordinate-space-anisotropy



momentum-space-anisotropy



$$\varepsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle}$$

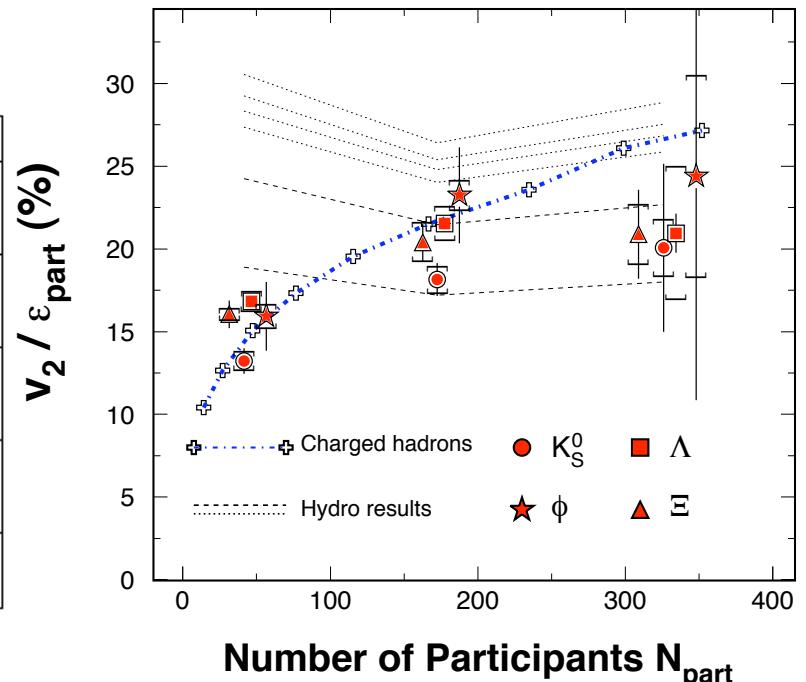
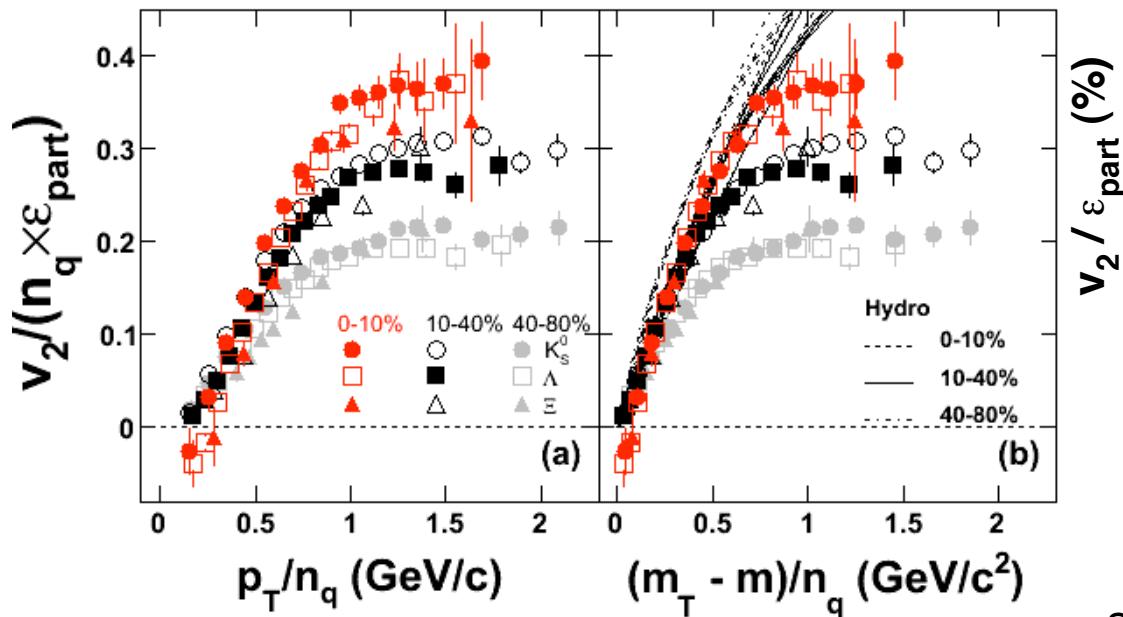
$$v_2 = \langle \cos 2\varphi \rangle, \quad \varphi = \tan^{-1} \left( \frac{p_y}{p_x} \right)$$

Initial/final conditions, EoS, degrees of freedom

# Centrality Dependence

STAR: *Phys. Rev. C77*, 54901(2008)

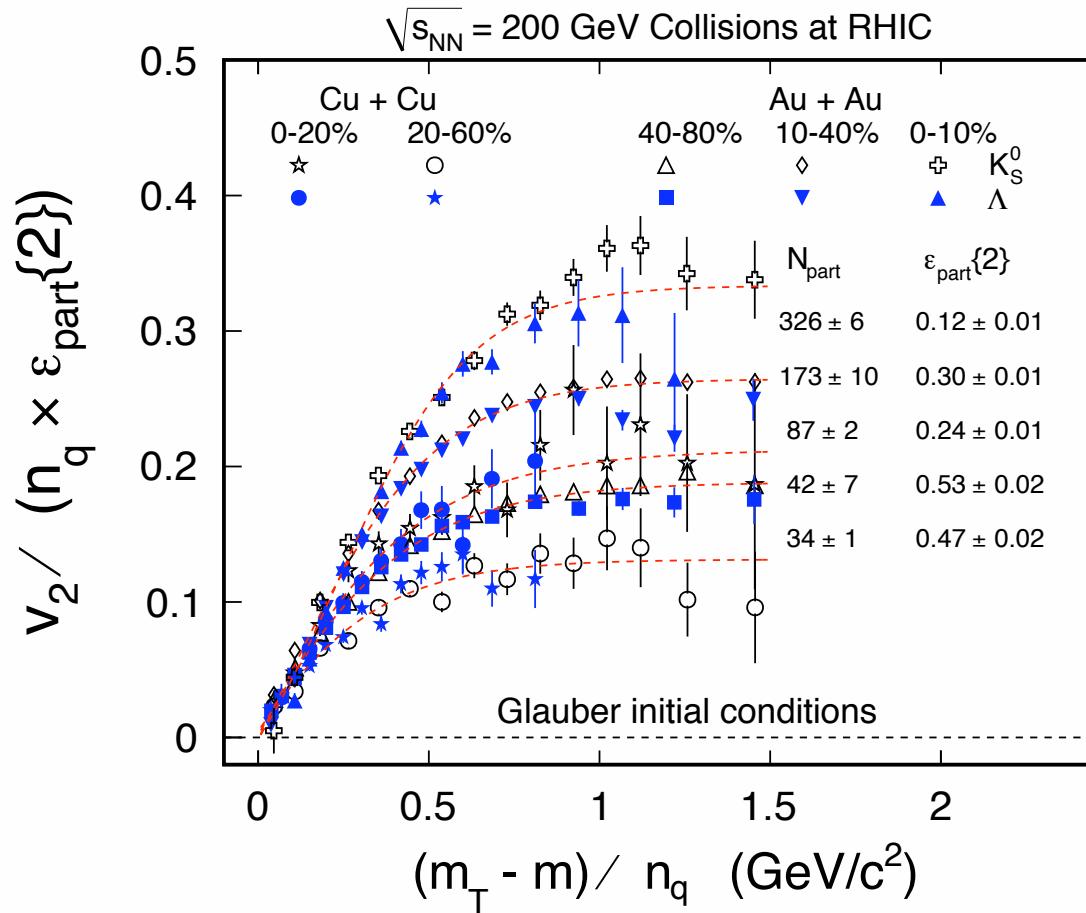
**200 GeV Au+Au**



S. Voloshin, A. Poskanzer, *PL B474*, 27(00).  
D. Teaney, et. al., *nucl-th/0110037*

- Larger  $v_2 / \epsilon_{\text{part}}$  indicates stronger flow in more central collisions.
- NO  $\epsilon_{\text{part}}$  scaling.
- The observed  $n_q$ -scaling does not necessarily mean thermalization.

# System Size Driven Collectivity

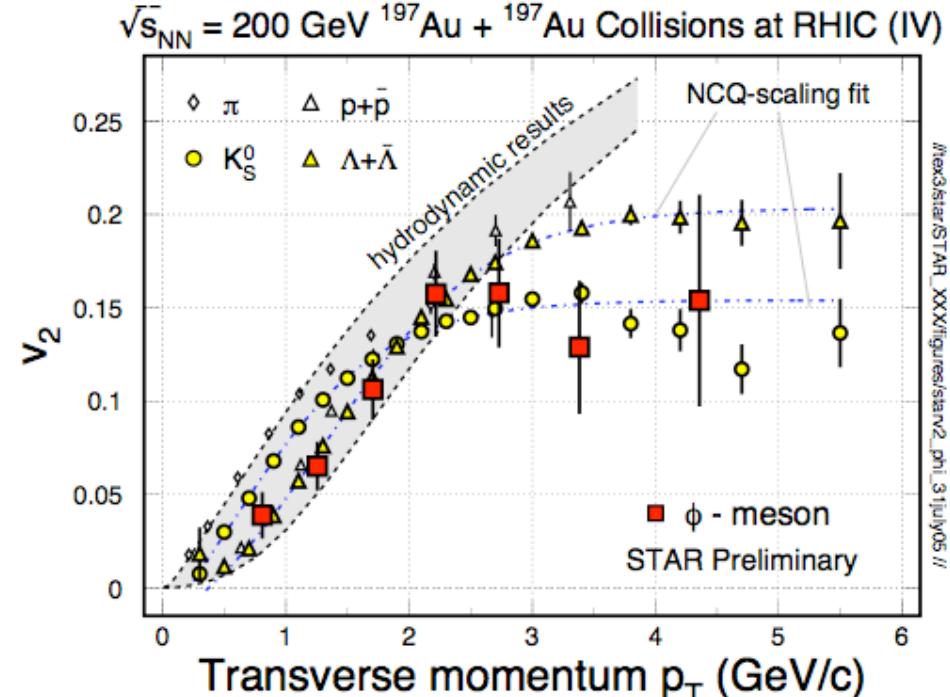
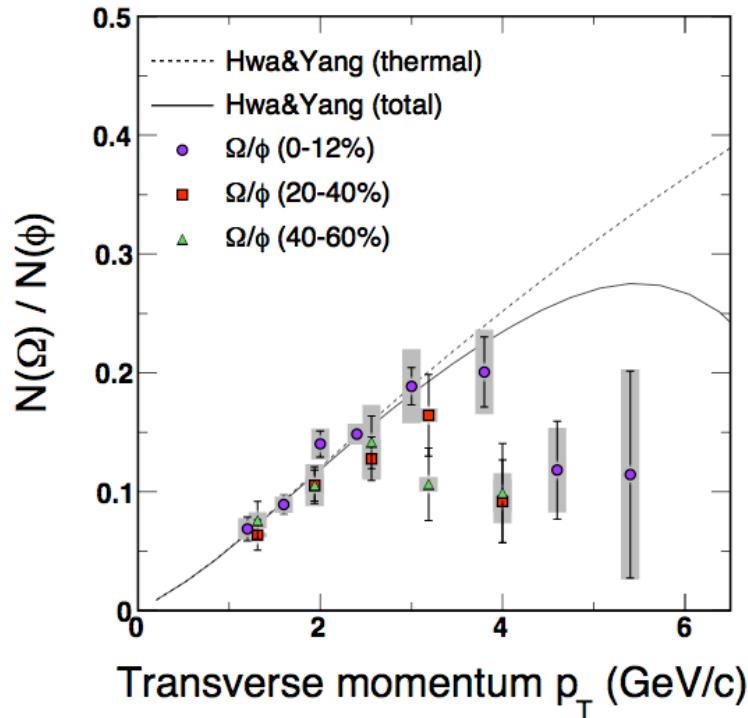


**Collectivity:** Driven by number of participants,  
NOT by eccentricity.

**Caution:** Local Equilibrium and p.l. claimers!

# $\varphi$ -meson Flow: Partonic Flow

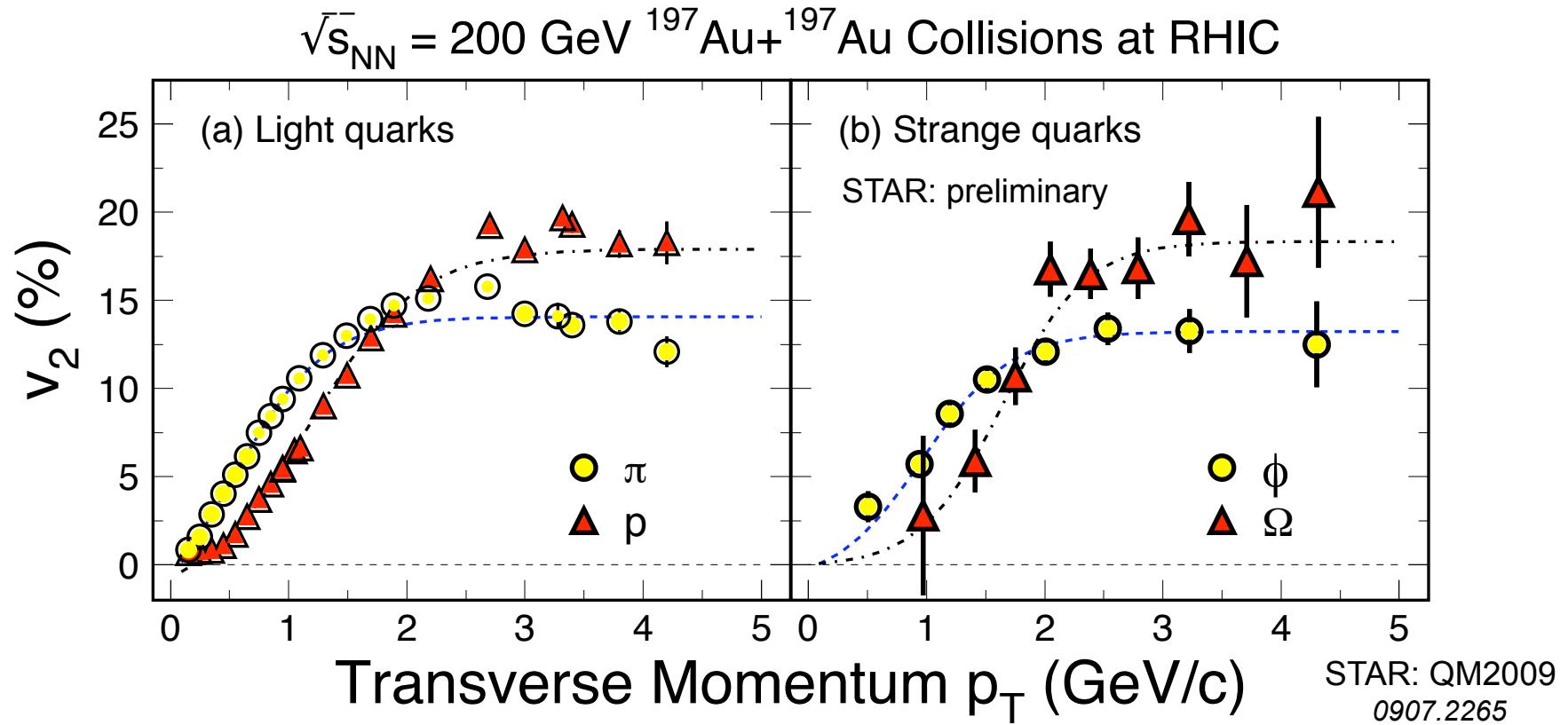
STAR: Phys. Rev. Lett. **99**, 112301(2007).



“ $\varphi$ -mesons (and other hadrons) are produced via coalescence of seemingly thermalized quarks in central Au+Au collisions. This observation implies **hot and dense matter with partonic collectivity** has been formed at RHIC”

STAR: Phys. Rev. Lett. **99**, 112301(2007)

# Partonic Collectivity at RHIC



Low  $p_T$  ( $\leq 2 \text{ GeV/c}$ ): hydrodynamic mass ordering

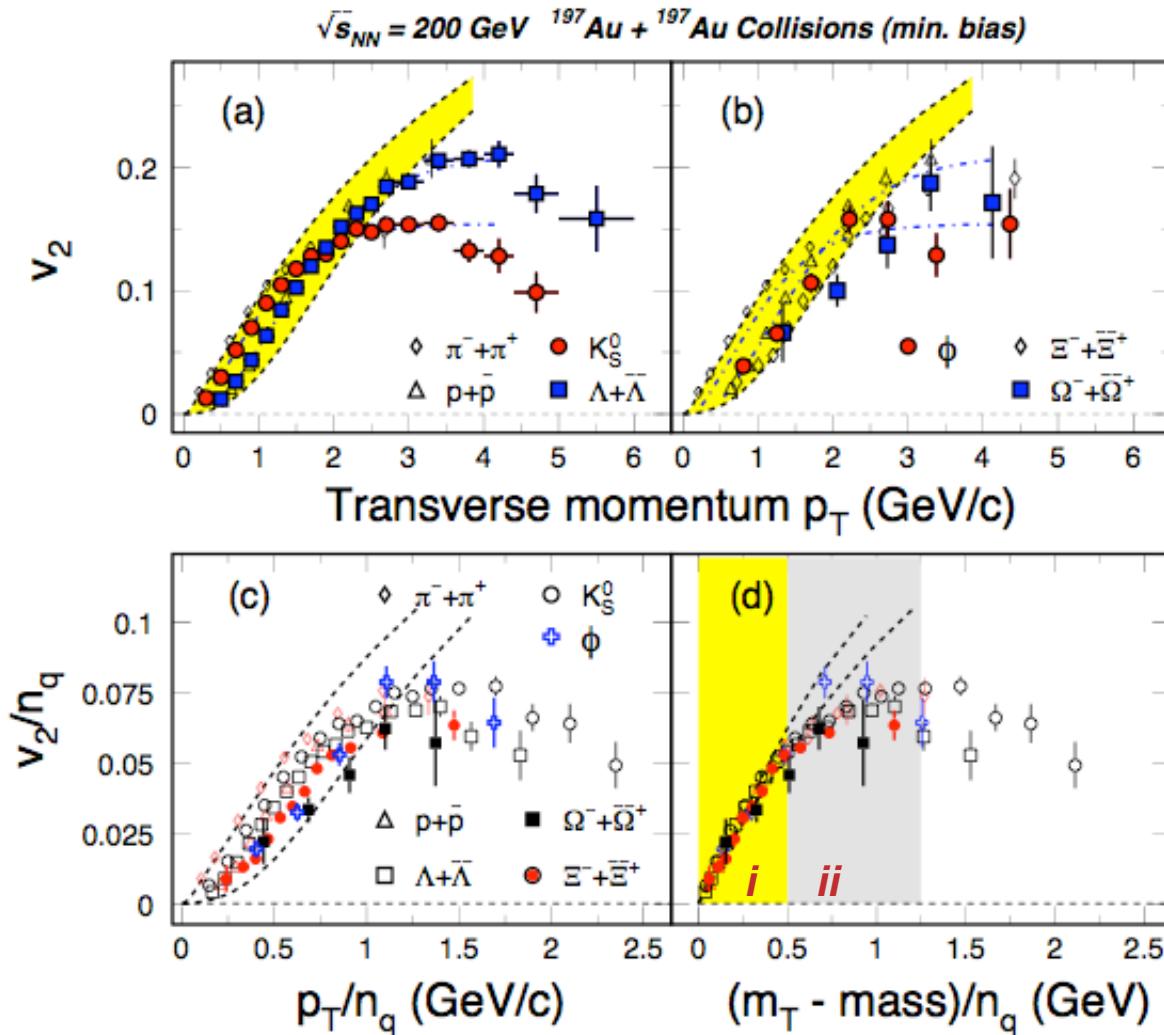
High  $p_T$  ( $> 2 \text{ GeV/c}$ ): number of quarks ordering

s-quark hadron: smaller interaction strength in hadronic medium

light- and s-quark hadrons: similar  $v_2$  pattern

**=> Collectivity developed at partonic stage!**

# Collectivity, De-confinement at RHIC



- $v_2$  of light hadrons and multi-strange hadrons
- scaling by the number of quarks

At RHIC:

- ➡  **$n_q$ -scaling**  
novel hadronization process
- ➡ **Partonic flow**  
De-confinement

**PHENIX:** *PRL* **91**, 182301(03)

**STAR:** *PRL* **92**, 052302(04), **95**, 122301(05)  
*nucl-ex/0405022*, *QM05*

S. Voloshin, *NPA* **715**, 379(03)

Models: Greco et al, *PRC* **68**, 034904(03)

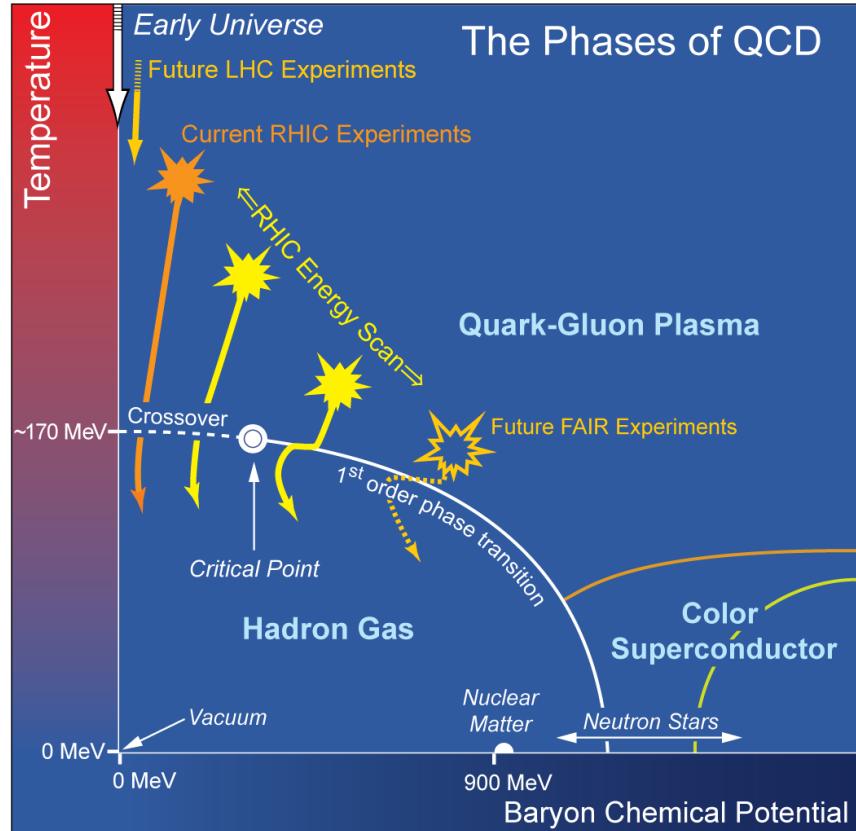
Chen, Ko, *nucl-th/0602025*

Nonaka et al. *PLB* **583**, 73(04)

X. Dong, et al., *Phys. Lett.* **B597**, 328(04).

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# The QCD Critical Point



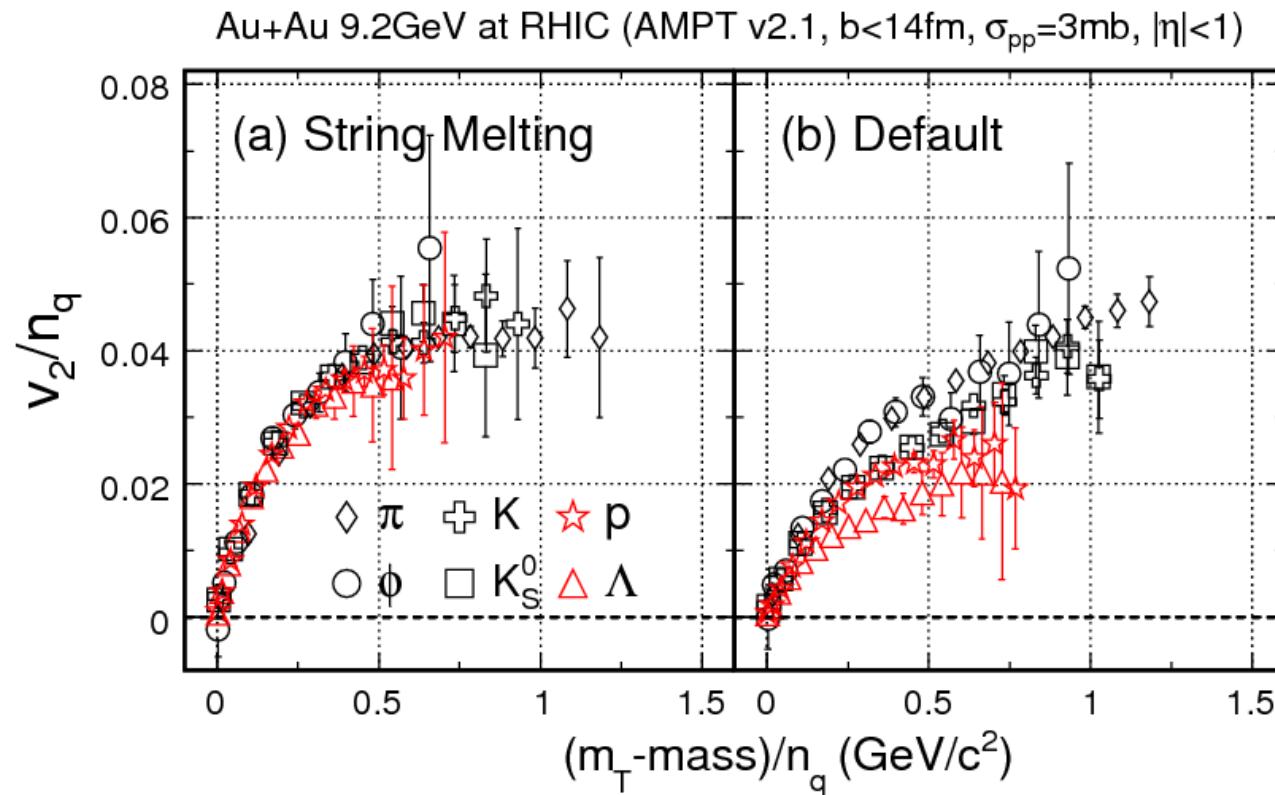
- LGT prediction on the transition temperature  $T_c$  is robust.
- LGT calculation, universality, and models hinted the existence of the critical point on the QCD phase diagram\* at finite baryon chemical potential.
- Experimental evidence for either the critical point or 1<sup>st</sup> order transition is important for our knowledge of the QCD phase diagram\*.

\* *Thermalization has been assumed*

M. Stephanov, K. Rajagopal, and E. Shuryak, PRL **81**, 4816(98); K. Rajagopal, PR **D61**, 105017 (00)

<http://www.er.doe.gov/np/nsac/docs/Nuclear-Science.Low-Res.pdf>

# Au+Au Collisions at 9.2 GeV AMPT (v2.1)

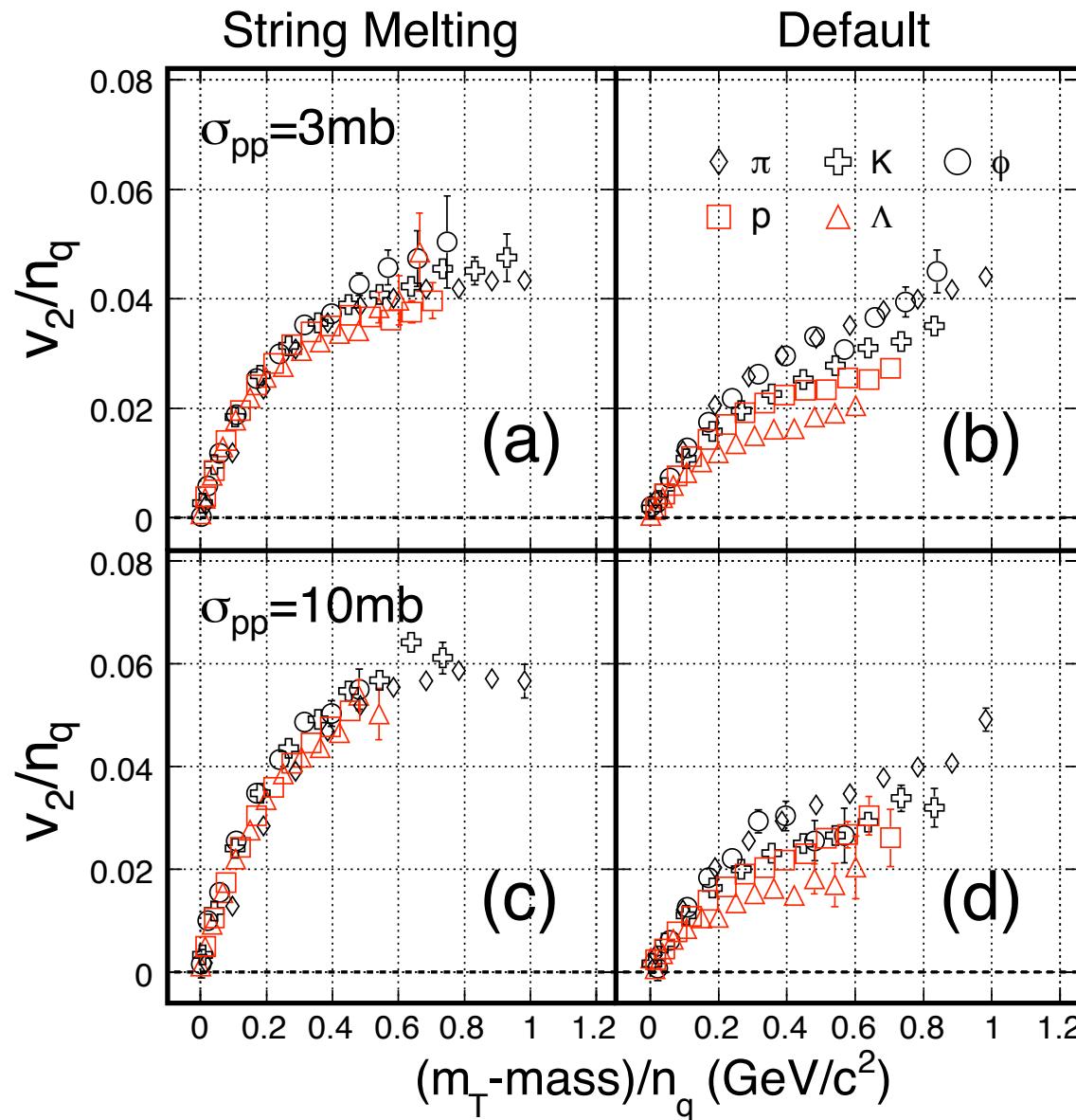


**(a) Patonic matter:** coalescence of massive quarks for hadronization

→ Clear NQ scaling in  $v_2$  !

**(b) Hadronic matter:** rescatterings amongst hadrons

→ No NQ scaling in  $v_2$  !



## AMPT model results:

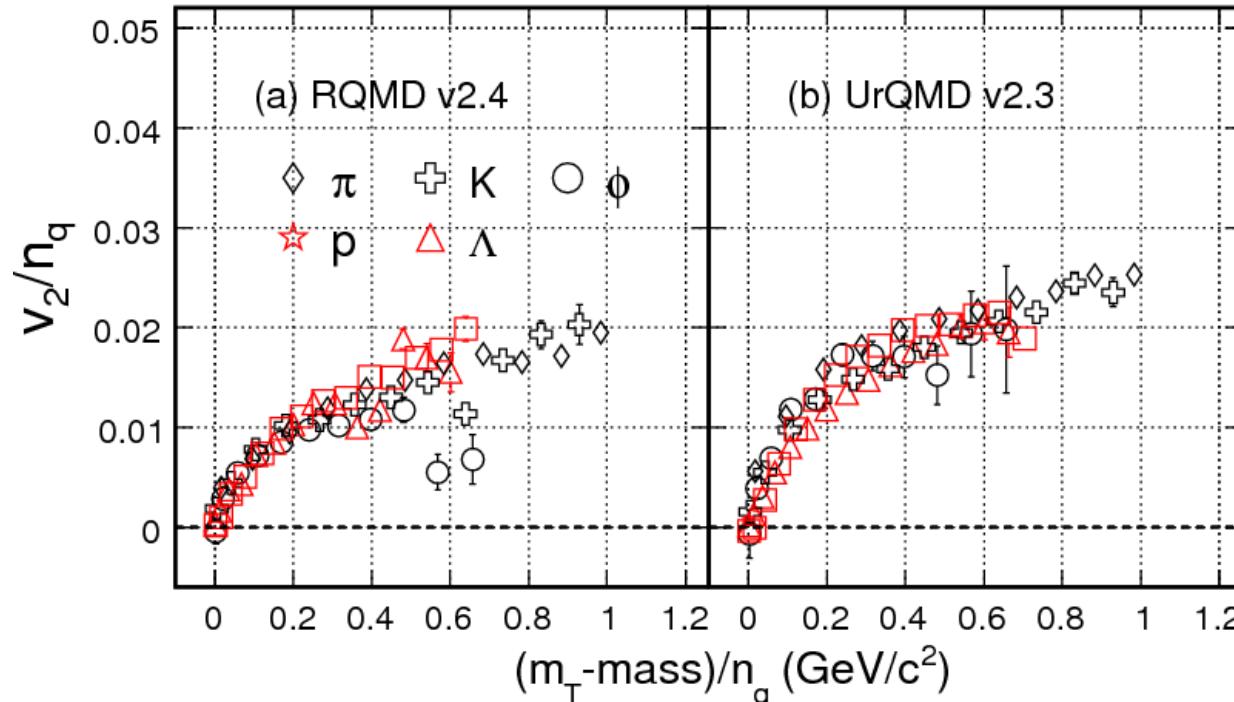
- 1) In AMPT, the scaling in  $v_2$  is independent of partonic cross sections
- 2) The amplitude of  $v_2$  depends on the value of the cross section

=>

**The beam energy dependence of the partonic cross sections will not affect the  $v_2$  scaling argument. Important for BES program.**

# RQMD and uRQMD Results

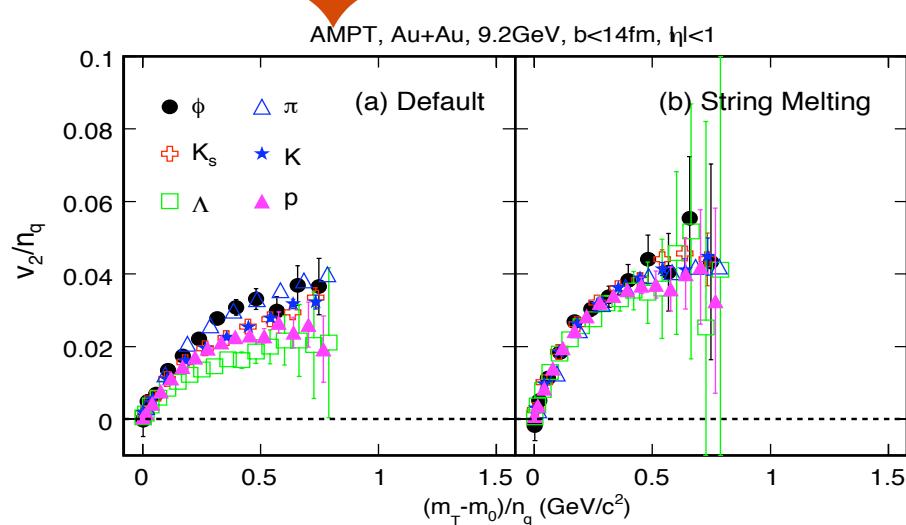
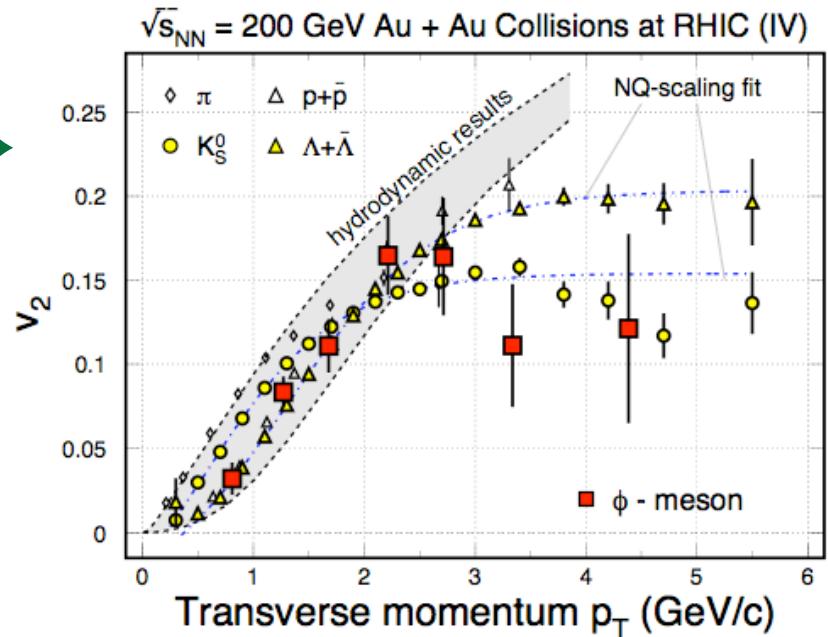
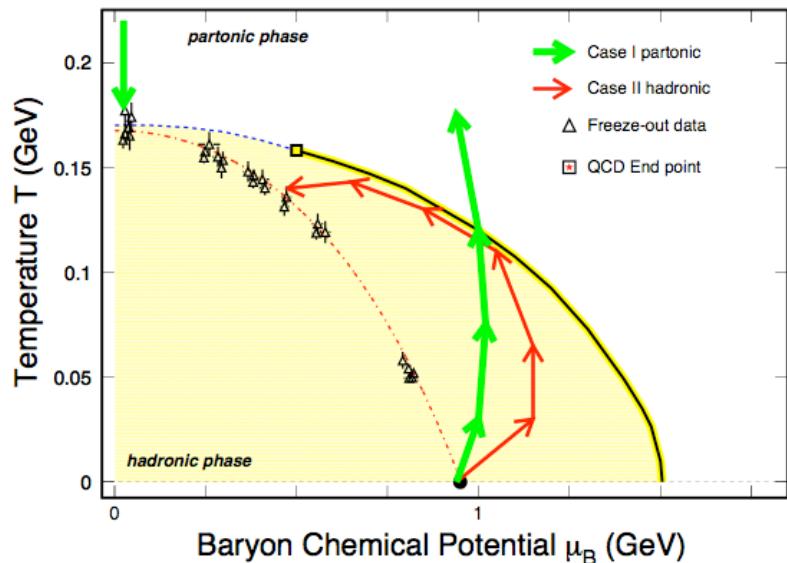
Au+Au 9.2GeV at RHIC,  $b < 14\text{fm}$ ,  $|\eta| < 1$



- 1) These hadronic models predicted a lower  $v_2(p_T)$  compare to that from AMPT hadronic mode calculations.
- 2) They also show a scaling better than that from AMPT hadronic mode calculations, due to the number of quark scaling in hadron cross sections used.
- 3) Multi-strange hadrons,  $\phi$  and  $\Omega$ , for example, are important for a clean measurement.



# Observable\*: Quark Scaling



- $m_\phi \sim m_p \sim 1 \text{ GeV}$
- $s\bar{s} \Rightarrow \phi$  not  $K^+K^- \Rightarrow \phi$
- $\sigma_{\phi h} \ll \sigma_{p\pi, \pi\pi}$

***In the hadronic case, no number of quark scaling and the value of  $v_2$  of  $\phi$  will be small.***

\* Thermalization is assumed!

# Summary

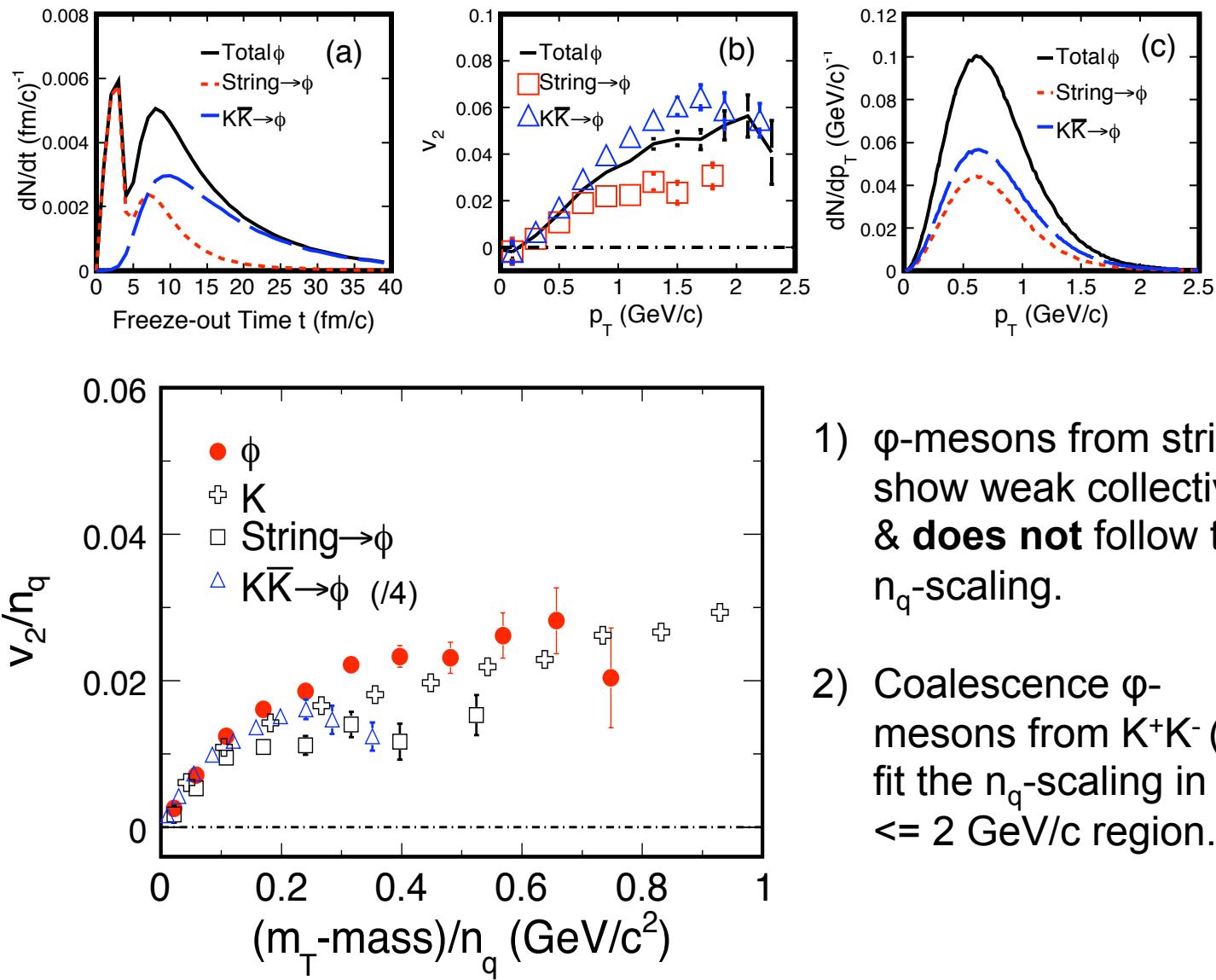
- 1) Number of quark scaling in  $v_2$ : partonic collectivity and de-confinement in high-energy nuclear collisions.
- 2) Scaling in  $v_2$ : partonic dof dominant  
No scaling in  $v_2$ : hadronic dof dominant
- 1) The multi-strange hadrons are particularly clean for the search,  $\phi$  and  $\Omega$ , for example.

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# Tests with uRQMD



- 1)  $\phi$ -mesons from string show weak collectivity & **does not** follow the  $n_q$ -scaling.
- 2) Coalescence  $\phi$ -mesons from  $K^+K^-$  (/4) fit the  $n_q$ -scaling in  $p_T \leq 2 \text{ GeV/c}$  region.